Implementation of the effect of turbines on water currents in MOHID Modelling System

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Thesis to obtain the Master of Science Degree in

Industrial Engineering

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September 2017

ABSTRACT

The present document describes the project of including into the hydrodynamic model of MOHID Studio application the effect of current energy extraction with turbines. This implementation intends to be a reliable tool for promoting renewable energies, in particular tidal energy, and allow users to study flow modification and energy extraction as well as other sub-consequent effects in a medium-big scale resolution (for example water level effect or sedimentation transport).

The implementation is thought for axial turbines that can turbine on both direction, with free rotation on the vertical axis and pitch control for the power harvested. It can work in 2D and 3D simulations, even though the turbine is only discretised in the vertical direction (for 3D simulations only), not in the horizontal plane. The horizontal resolution, in order to obtain useful results, must be as little as the dimension of the turbines blades. Biggest size of the grid works fine but graphically the results are inaccurate.

The programming is made in Fortran90, the same language as MOHID Studio application, and the code is Open Source, so it is not included in this memory, it can be found in MOHID github repository [13].

Keywords: **[Tidal energy] [Current Energy] [MOHID Water] [MOHID Studio] [Turbine] [Finite Elements]**

ACKNOWLEDGEMENTS

Thanks to all the department of MARETEC for the help during the development of this thesis. Especial thanks to Ramiro Neves for tutoring the project and giving advice in the development, to Ricardo Miranda for the assistance and teachings in the programming and to Guillherme Franz and João Sobrinho for the help in MOHID as a user.

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1. INTRODUCTION

1.1. GENERAL OVERVIEW

To contextualize this project, a wider overview of the nowadays “energy problem” should be provided. Human activity, mainly the fact of burning fossil fuels for obtaining energy, is affecting in a non-sustainable way the environment: CO2 pollution is reaching record values, the mean global temperature has increased in almost 1 ºC since 1880 [1], the urban air-pollutions is reaching unhealthy levels, etc. And this are just the main ones, the list is quite huge, and small variations can have terrible environmental consequences in the ecosystem and all the living species on the planet, including humans. Some changes have to be done in order to build a cleaner and more sustainable energy system able to deliver worldwide secure, affordable and sustainable energy.

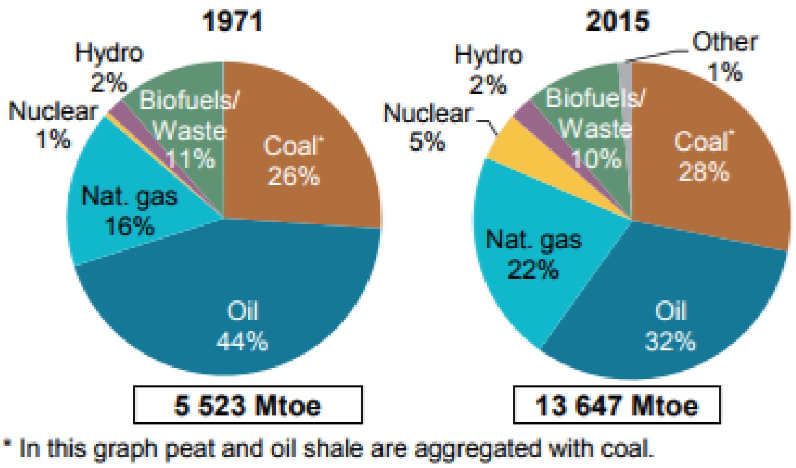

Figure 1. Total primary energy supply by fuel in 1971 and 2015. In other there are included renewable sources as geothermal, solar, wind, etc. Source: IEA [2]

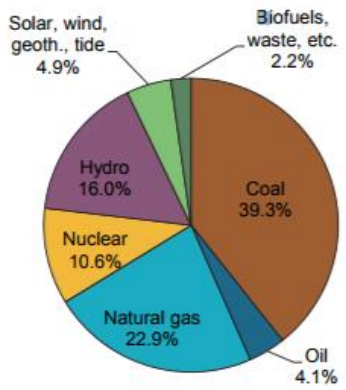

Figure 2. World gross electricity production (%) by source in the year 2015. Source: IEA [3]

According to the last data provided by the IEA (International Energy Agency), the primary energy supply all around the world mainly proceed from fossil fuels (figure 1). The same happens with electricity production (figure 2). Taking into account the fact that the world population is expected to grow up to 9 billion for the 2050 and the technological development of emerging countries, the world energy demand is compelled to increase, following the actual tendencies as is shown in figure 3.

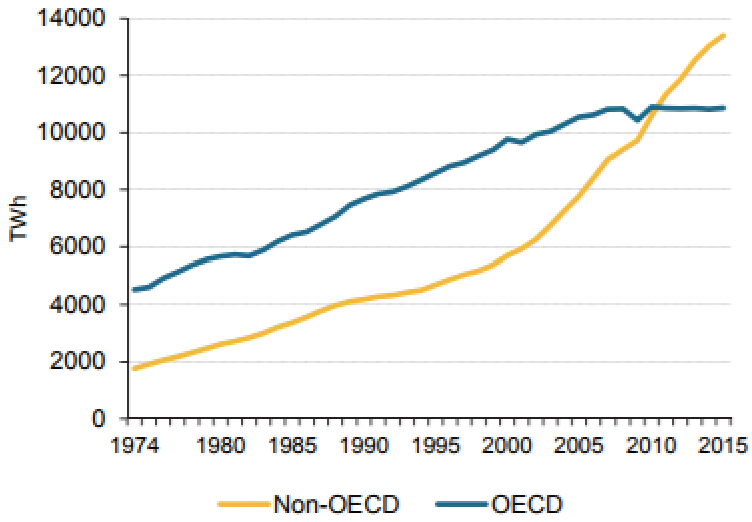

Figure 3. World total gross of electricity production of OECD and non-OECD countries. The OECD, Organisation for Economic Cooperation and Development, is composed by 35 states, including basically the world's most advanced countries. Source: IEA [3]

In this graph is appreciated how the OECD countries gross energy production increase slightly in the last 5 years compared to the non-OECD countries. An interesting fact is that the OECD countries had experimented a small decrease in electricity production from fossil fuels [3] and an increase in renewable sources [4], so there is a willing to change the energy system towards a renewable one, but for the moment, is not sufficient. The actual energy system has an expiring date and need to change quickly. An energy sustainability between the environment, the social welfare and the economy is needed to procure a global energy system compatible with a sustainable development. The main issues are: equity in access and affordable energy services, environmental impact, greenhouse gas emissions and resource preservation. To achieve that, the next points should be take into account:

- Restrain the demand/consumption. Make a responsible use of energy and resources.
- Improve technological efficiency of production, transportation and consumption points.
- Increase the use of renewable energy technologies.

The implementation developed is thought to boost a renewable source of energy, water currents. Renewable energies are the cornerstone for a sustainable future, and due to the increasing demand of electricity consumption in the years to come, the electricity industry is one of the main points to take action on. At the present time around 22-24% (figure 2) of the electricity comes from renewable sources, and it is estimate to grow in the years to come. The question is if the change will be in time.

There are many kinds of renewable energies: biomass, eolic, geothermic, marine, tidal, solar, etc. Several of this renewable sources present the challenge of being weather dependant, which difficult its development. The electrical greed needs stable energy, and if it can be on demand, better. Renewable energies like wind are the opposite, they cannot produce energy on demand, only when it’s windy. They cannot be used as the base of an energetic system because of it unpredictability. This is one of the main handicaps of some of the more used renewables energies sources today.

The other big challenge is the cost. A lot of renewable technologies are actually in a prototype and development phase, and the conditions (in current energies for example, in the actual state of development, they need high average velocity to be economically worthy) to make them worthy economically speaking are just too strict. There is where energy policies came in, they have a huge influence on the development of renewable energies though they are the ones that can obviate the economic part and also, with the properly development and research, make them more efficient and profitable.

Is the duty of the people, governments, research centres, companies, of everyone to boost renewable energy towards fossil fuels, in a sustainable way. This effort is necessary for a sustainable future, for the planet itself. Today is the money who rules the energy system, but this needs to change, energy lobbies need to be faced in detriment of a better quality of life and respect of the environment. The planet have enough renewable resources in order to provide the global energy needs, it only has to be done properly.

This thesis presents the following layout. First, it describes the current energy and introduce the software used and where the implementation is programed. Second, the physical concepts and mathematical formulation of the 3D hydrodynamic model that is used in MOHID. Third, the physical and mathematical formulation made for the current turbines is explained. Fourth, the model is applied on channels in different layouts to test the implementation and proof its reliability. Fifth and final, there are the conclusions and an explanation of the next steps in order to improve this implementation.

1.2. CURRENT ENERGY

The oceans represent a huge source of renewable energy. Nowadays, this energy is obtained through six different ways: waves, tidal range, tidal current, ocean current, ocean thermal energy and salinity gradient. The technologies in charge to take profit of this kind of energies, compared to other kind of renewable technologies, are at an early stage of development. In fact all ocean energy in general is in an early stage [5], with the exception of tidal barrage. There are then, two ways to produce energy from the currents in the ocean, tidal currents and marine currents. There is a third way of current energy, rivers.

The only difference of these three sources of water currents are the phenomena that origins them, but the energy that can be extracted is the same in all of them, is only kinetic energy, and can be expressed as:

$$P = \frac{1}{2} A \rho U^3 \qquad \text{Eq. 1}$$

Where U is the velocity of the flow through the specific surface A. From this amount of energy only a portion can be extracted with turbines, which is modelled with a power coefficient. Tidal energy is the most developed [6] in the group of current energy extraction so a more detailed explanation is given.

Tides can be defined as the oscillatory motion of the ocean in which the mass of the ocean rises and falls alternately in a regular way. These oscillations are mainly due to the gravitational interaction of the Moon and the Sun on the Earth and the rotation of the Earth. These forces causes an alternation of potential energy which creates horizontal currents of water that we call rise-fall and flood-ebb currents. This currents and difference of water level can be used to generate electricity basically in two main procedures: either harnessing its potential energy using tidal barrages or its kinetic energy using stream devices, turbines. But in this thesis only current energy is object of study. In the figure 4 we can find the places were the biggest tidal currents can be found, taking into account that they appear near the coast caused by the narrowing of the geography, which causes high velocities with the rise and fall of the tides.

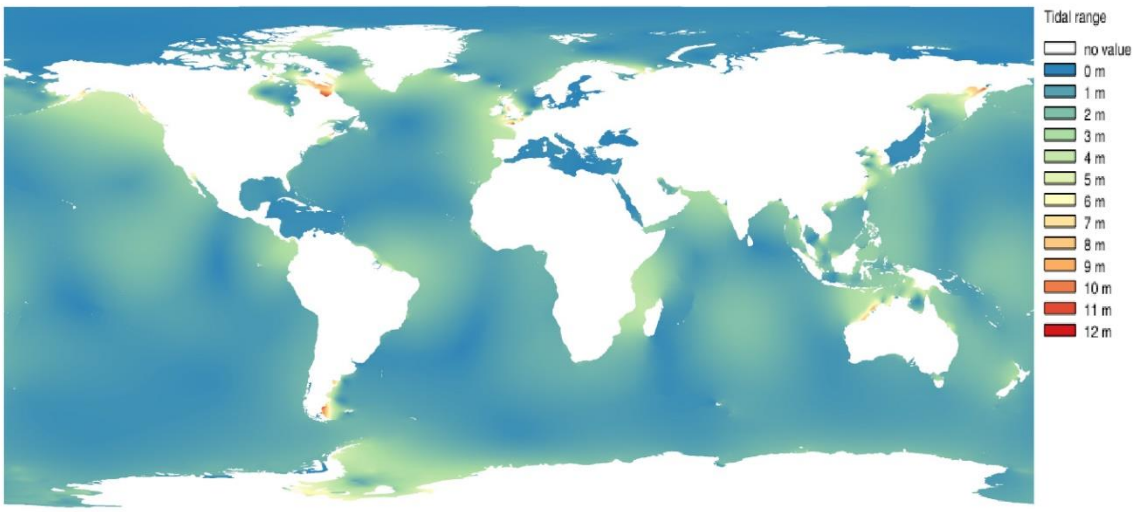

Figure 4. Tide range all over the world. This map shows the places with more tidal range and in consequence, they are candidates to have high velocity currents Source: https://www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/

For marine currents, the only near-shore large-scale current swift enough to drive large electricity-generation are the subtropical surface western boundary currents [7], at the actual state of this technology development. For river currents, rivers with huge discharges as the Amazon are possible emplacements. Current turbines offers a less impact alternative of the classical hydropower centrals.

One of the strong points of this source, beyond its accessibility, is its predictability. Tides, for example, are more predictable than wind or sun, and they can be used in a future as base energy in the countries energy systems. Also, as the turbines work with in-stream currents, what means that the current in which the turbine is placed is due to natural causes, they impact compared with hydropower centrals or tidal barrage is reduced.

Even though current streams are a renewable sources of energy, as all of the renewable energy technologies, they aren't environmentally friendly by definition [6]. All the activities involved in the manufacturing and maintenance have an impact on the environment. Their life cycle has an impact on the environment and further studies should be done in order to know they real impact. For example, the alteration in flow patterns cause a modification in the sediment transportation and in water level, and both effects have a direct impact on the environment. Also there is the environmental impact to the fauna habitat of the emplacement where the turbines will be placed, it can cause physical damage to the animals and also the noise caused by the turbines can disturb them. In definitive, even if they are renewable sources, they need to be implemented with caution and responsibility, watching all the possible effects.

1.3. MOHID Water

MOHID is an environmental modelling system dealing with transport and biogeochemical transformation processes in complexes geometries, developed at the Marine and Environmental Technology Research Center (MARETEC) at Instituto Superior Tecnioc (IST). It has multiple functionalities and can deal with multiple physical conditions. The actual MOHID model is able to deal with 1D, 2D and 3D simulations, Eulerian or Langrangian approaches and different vertical coordinates and cell geometries. It allows to run nested models in order to allow users to study local areas obtaining the boundary conditions from the father model [8].

It has two main cores, MOHID Land and **MOHID Water**, and can be used to simulate a wide range of processes as sediment transport, water quality, infiltrations, channel flows, etc. The implementation programmed in this thesis only affects the MOHID Water core, where the hydrodynamic model is programed.

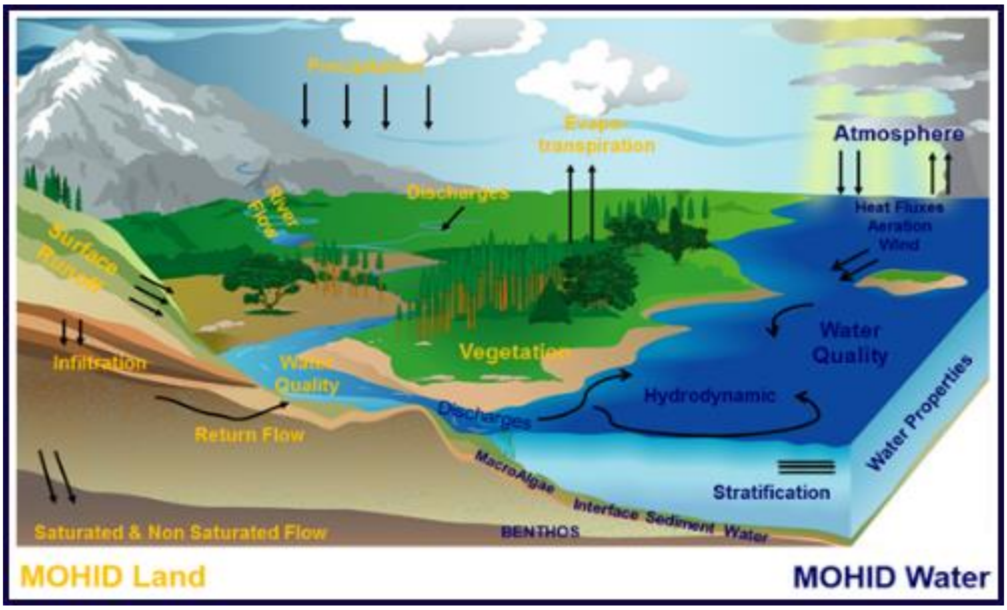

Figure 5. MOHID graphical representation. Source: http://www.actionmodulers.com

Nowadays, the whole model is programmed in ANSI FORTRAN 95 with an object oriented philosophy. It is a really complete model, with more than 40 modules and 1000 thousand code lines. The code is open source with the idea to allow the inclusion of new developments, as it happens to be with this implementation.

In conclusion, MOHID is a really complete model that covers a long list of processes and has a huge quantity of implementations and capabilities. It has a lot of pre-processing and post processing tools, and even deep knowledge of the processes involved is needed in order to make the simulation correctly. All this makes of MOHID a reliable decision support tool [9] which have been used for some coastal projects, and nowadays is the current working tool of MARETEC research centre.

1.4. OBJECTIVE

The main objective of the project is to implement in the MOHID hydrodynamic model the effect of extracting kinetic energy of water currents with turbines, providing users the possibility to see energy extraction and flow modification. The idea is to make a reliable tool that can be used by others in the MOHID application for any kind of studies that includes turbines and currents. As the project is Open Source, the implementation can be improved by other users in the future.

1.5. SCOPE OF THE PROJECT

The scope of the project can be summarised in the next goals:

- Give a global panorama of the actual energy system and expose the idea of why tidal energy, tidal currents specifically, should be taken into account in the sustainable energy system of the future.
- Explanation of the implementation and all the simplifications considered.
- Program the implementation. The implantation should be programmed so it can be useful in further simulations, not only for this project.
- Verification of the implementation. It will be tested in different environments with MOHID Studio app and the results will be analysed.
- Leak points of the implementation and improvement points.

2. DEVELOPMENT

2.1. HYDRODYNAMIC MODEL

The hydrodynamic model of MOHID solves the three-dimensional incompressible primitive equations assuming hydrostatic equilibrium, Boussinesq and Reynolds' approximations [8]. All the equations here are written in the differential form and Cartesian coordinates.

The momentum balance equations, Navier-Stokes, for horizontal velocities are:

$$\frac{\partial u}{\partial t}+\frac{\partial (uu)}{\partial x}+\frac{\partial (uv)}{\partial y}+\frac{\partial (uw)}{\partial z}-fv=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(A_H\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_V\frac{\partial u}{\partial z}\right) \qquad \text{Eq. 2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}+\frac{\partial (vw)}{\partial z}+fu=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(A_H\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_V\frac{\partial v}{\partial z}\right) \qquad \text{Eq. 3}$$

The vertical momentum, if we assume hydrostatic pressure (neglecting vertical flow accelerations and diffusive transport), becomes:

$$\frac{\partial p}{\partial z}+\rho g=0 \qquad \text{Eq.3}$$

The continuity equation, with incompressible fluid (constant density), according to the Boussinesq approach is:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \text{Eq.4}$$

The variables u, v and w represent the components of the velocity vector in the x,y and z directions respectively; f is the Coriolis parameter, A_H and A_V are the turbulent viscosities in the horizontal and vertical directions. The ρ_0 and ρ are the reference density and density respectively, and the p is the pressure.

The density is computed by the UNESCO equation of state as a function of the salinity, temperature and pressure. The turbulence is compute as a one-dimensional model, based on the GOTM model for the vertical and on empirical formulation for the horizontal.

In the model, there are two layers that differ from the rest: the bottom and the free surface layer. In the bottom, the shear stress can be computed with the assumption of a logarithmic velocity gradient and in the surface the shear stress from the wind can be also computed.

For the spatial discretisation MOHID uses a finite volume approach to discretize the equations. The discrete form of the governing equations is applied macroscopically to a cell control volume. It is interesting to highlight that the procedure of solving the equations is independent of the cell geometry, allowing almost all kind of shapes of the cell.

It is important to know that the grid is staggered in the horizontal in an Arakawa C manner [10]. For example, horizontal velocities are located in the centre-west (u-velocities) and south (v-velocities), while elevation is placed on the centre (figure 6). It is important for knowing where the calculated values and the interpolated ones are.

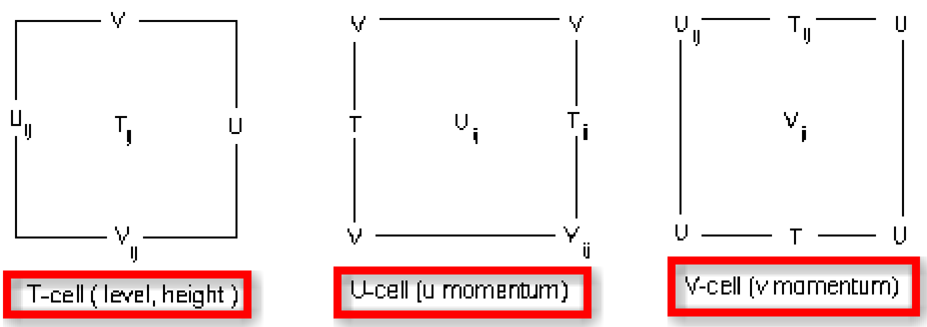

Figure 6.Arakawa C manner placement of the calculated parameter in a grid cell. Source: wki.mohid.com

The model admits different vertical coordinates as Sigma, Cartesian, Lagrangian, Fixed Spacing and Harmonic, been the Sigma and the Cartesian the more used ones.

Another important point is the temporal discretisation. It is done by a semi implicit ADI (Alternate Direction Implicit) algorithm. This algorithm computes each velocity component alternatively implicitly and explicitly. This allows preserving the stability advantages of implicit methods without the drawbacks of computational expensiveness and associated phase errors. Is it possible to choose between two different discretizations [8], the Abbot scheme and the Leendertsee scheme.

2.2. DESCRIPTION OF THE IMPLEMENTATION

2.2.1. Design considerations

The most desirable approach for numerically model the impact of current turbines in the flow for current energy extraction would be to employ a full three-dimensional hydrodynamic model with an accurate representation of the flow-structure interactions between the current flow and the turbine. An accurate representation means to work with a high resolution in the discretisation of the domain (vertical and horizontal) where the turbine are located, what implicitly means a high resolution in the turbine geometry. Also, it should take into account that the geometry rotates in the vertical plane (the blades of the turbine for axial turbines) and also can rotate in the horizontal plane, to adapt the direction of the turbine to the flow and maintain the perpendicularity between them. This implementation, at first sight is quite difficult to make by its own, but even that, there is a problem in the relative scales of the processes involved. To model the turbine interaction with the flow a small size of the mesh is needed while for modelling tidal flow processes the resolution is far smaller (big size of cells). And we have the same issue with the temporal discretisation.

The idea then, is to provide the best approach possible to model the tidal energy harvesting and the impact of turbines in the flow. For that it is important to find the balance between the spatial discretisation and the implementation in order to be able to join the processes of, for example, tides and turbines in the same simulation and have useful numerical and visual results. The implementation will be a 2D and 3D model in order to take profit of the 3D hydrodynamic model of MOHID explained in the point before and make the implementation more flexible in the future simulations that can include this turbine approach. Working only in 2D will be a huge limitation for the potential of MOHID model.

So, the main design considerations are a 2D-3D model, for axial turbines that can turbine in both directions and with free rotation in the vertical axis so the stream velocity is always perpendicular to turbine.

2.2.2. Model fundamentals

There are several approaches for model the effects of the turbine in a 2D or 3D hydrodynamic model. Most of them are based on the same premise, represent the turbine as a momentum sink by adding a reaction force (F_T) into the hydrodynamic model.

$$P_T = F_T U \qquad \text{Eq.5}$$

The power of the turbine can be interpreted as the product of the reaction force and the stream velocity. The power of the turbine is an input parameter, and the velocity is given by the hydrodynamic model, so it is possible to calculate this reaction force and include it in the model to proceed with the simulation. To simulate the turbine, two main parameters need to be introduced [11]:

- The thrust force produced by the turbine rotor due to energy extraction, eq. 6.
- The power extracted by the turbine, eq. 7.

$$F_T = \frac{1}{2}\rho A_T C_T U^2 \qquad \text{Eq.6}$$

$$P_T = \frac{1}{2}\rho A_T C_p U^3 \qquad \text{Eq.7}$$

The ρ is the density, the A_T is the area swept by the blades, C_T is the thrust coefficient that quantifies the force exerted by the turbine to the flow and C_p is the power coefficient that quantifies the amount of power extracted from the flow. The drag force exerted by the structure of the turbine is not contemplated in this model. Some models use the same coefficient for thrust and power, what means that the work done against the flow is the same as the energy extracted from it but, as is expected, thrust coefficient have to be greater than power coefficient [12].

$$C_T = \begin{cases} 0 & \text{sii} \quad U \le U_C \\ C_{T0} & \text{sii} \quad U_C < U \le U_D \\ C_{T0}\dfrac{U_D^3}{U^3} & \text{sii} \quad U > U_D \end{cases} \qquad \text{Eq.8}$$

For the power coefficient, the parameterisation is the same:

$$C_P = \begin{cases} 0 & \text{sii} \quad U \le U_C \\ C_{P0} & \text{sii} \quad U_C < U \le U_D \\ C_{P0}\dfrac{U_D^3}{U^3} & \text{sii} \quad U > U_D \end{cases} \qquad \text{Eq.9}$$

C_{p0} and C_{T0} are the design values for each coefficient and U_C and U_D are the cut-in and design speed.

In the figure 7 the parameterization of the power coefficient is plotted, for the thrust coefficient it will be equivalent. Both coefficients are programmed with a security factor of 15% of the velocity cut-in speed, avoiding oscillation values of the thrust force and power. When the turbine starts working, $U > U_C$, the reaction force may decrease the velocity again under the cut-in speed. With 15% of security factor, the turbine continues to produce energy and exert reaction force till the velocity modulus U, decreases under $0.75U_C$. Once it decreases below this value, it has to increase again over U_C.

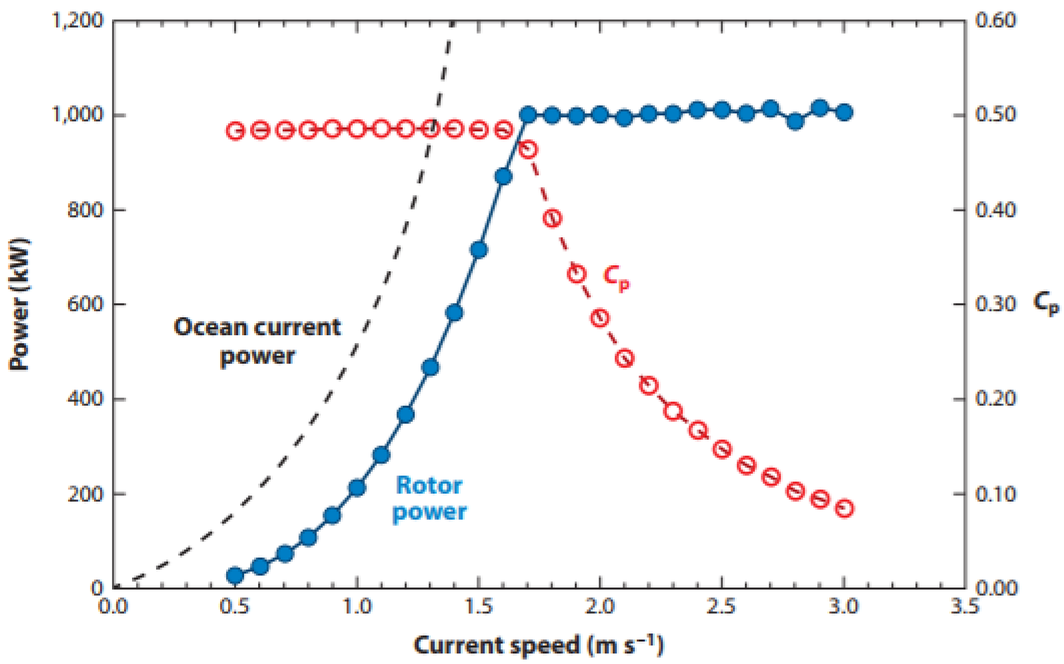

Figure 7. Power coefficient and power extraction evolution with current speed. Source: [7]

The energy extraction is calculated as the integration in time of the product of power and time differential. With a constant value of the time interval of the simulations, the equation for the energy is:

$$E_T = \sum_{i=0}^{n} P_T \cdot \Delta t \qquad \text{Eq.10}$$

Where n is the number of iterations and Δt is the time step.

2.2.3. Discretisation

In this implementation, the spatial discretisation is only on the vertical direction. As a result, the force excreted by the turbine is a punctual force and the calculation is made with the equation 6. The non-discretisation of the model in the horizontal axis simplifies quiet a lot the model and the perpendicularity between the turbine and the flow is implicitly assured.

$$A_{T_K} = \frac{r^2}{2}\theta - r\cdot\sin(\frac{\theta}{2})\cdot d - \sum_{k=1}^{k} A_{T_{K-1}} \qquad \text{Eq.11}$$

The vertical discretisation is made through the equation 11, providing a better approach of the thrust value in the vertical direction. In the figure 8 a visual croquis of the discretisation can be appreciated.

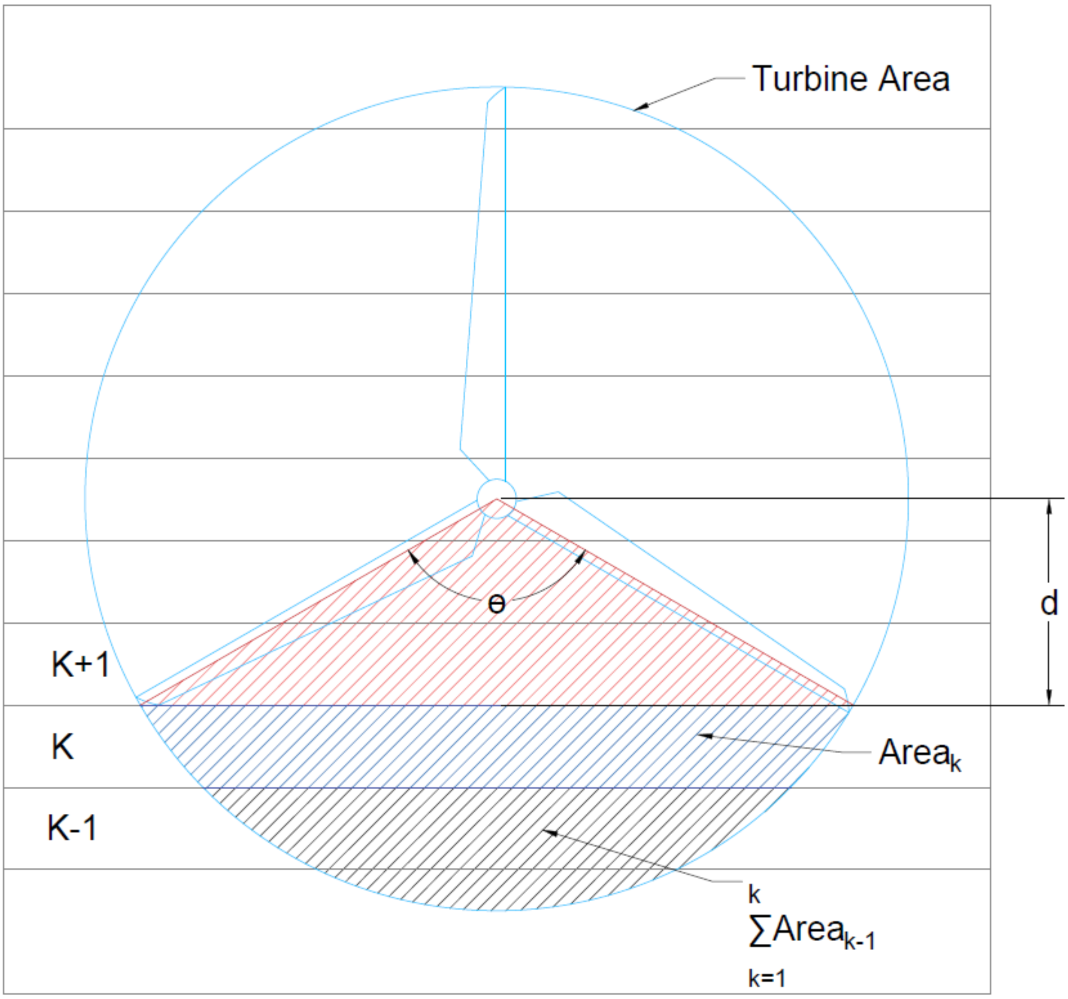

Figure 8. Vertical discretisation of the turbine area. Own source.

The force excreted by the turbine is calculated with the velocity of the flow in each layer while for the power, the velocity is an average value between the layers that contain the turbine. So, the equations 6 and 7 can be rewritten, for a turbine placed in the cell (I,J) coordinates, as:

$$\vec{F}_{T_K} = \frac{1}{2}\rho A_{T_k} C_T U_k \vec{U}_k \qquad \text{Eq.12}$$

$$P_T = \frac{1}{2}\rho A_T C_p U_{AV}^3 \qquad \text{Eq.13}$$

Where $\vec{U}_k$ is the velocity vector of the turbine in an Arkawa C manner (the u component in the centre of the West face and the v component in the centre of the South face). U_k is the velocity modulus and U_{AV} is the average modulus velocity of the k layers of the cells in the coordinates i, j that contain the turbine, calculated as:

$$U_{AV} = \frac{\sum_K A_{T_K} * U_K}{\sum_K A_{T_K}} \qquad \text{Eq.14}$$

The last thing left to specify is where the velocity modulus U_K is calculated. There are two ways, both of them valid. The first one is to calculate it in the middle of the cell. Taking into account the Arakawa C grid, the velocity modulus will be calculated with the velocities shown in the figure 9. This option makes that with the semi-implicit algorithm used in the model, the modulus value variations between u (velocity component in the x direction) and v (velocity component in the y direction) are minimal. Then, for calculating the thrust force in the nodes of the u and v velocity components (where the hydrodynamic model of MOHID calculates the velocities), we are using a velocity modulus not calculated in these points. The other one is to calculate the velocity modulus in the same point where the velocity components u and v are calculated, the centres of the West and South faces respectively. As can be appreciated in the figure 10, the modulus is calculated in each direction by the velocity components of the surrounding cells. With this option we are actually calculating (is an interpolated value also) the velocity modulus in the points where the velocities of the hydrodynamic model are computed. The issue is that we have different values of the velocity modulus when the model is computing the u component or the v component, as the calculations are made in different points.

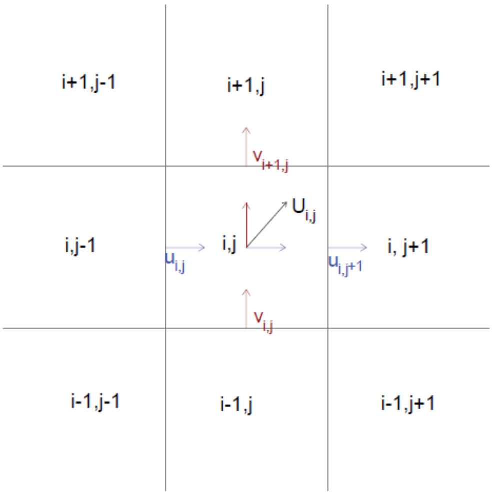

Figure 9. Option 1 for computing the velocity modulus in the cell. In this case the velocity modulus is calculated in the centre of the cell. Its value is the same when the model is computing one component of the horizontal velocity or the other. Own source

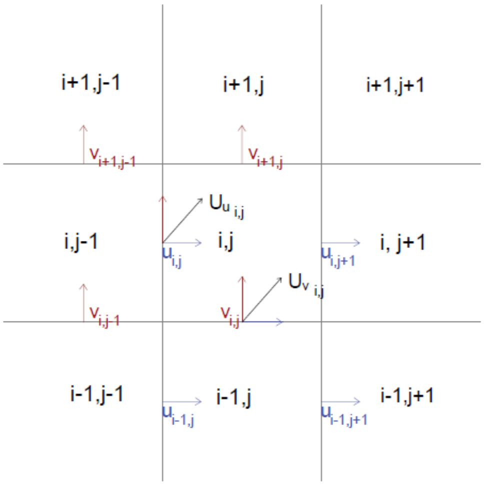

Figure 10. Option 2 for computing the velocity modulus in the cell. Here the velocity modulus is different. When the model computes the horizontal velocity component (u) the modulus is calculated in the same point where the u component is computed. The same happens with the v component. Own source.

The option one have the facility that the value calculated in the centre don't oscillates so much between the computing of the velocities and forces in each direction. The problem is that you are taking into account the velocity downstream the turbine, so the thrust force have already been taken into account. In small grid size this effect is emphasised, provoking lower power's output. The option two is different. The velocity taken into account to compute the thrust force and power is upstream. The problem is that with big cell sizes and depending of the direction of the flow the value oscillates more. In this implementation the first option have been chosen for the calculating of the velocity modulus even though it gives a more conservative results.

2.2.4. Output data

To sum up, the implementation is a 2D-3D model for axial turbines (with pitch blade control, able to turbine in both directions) and not discretized in the horizontal domain. To visualise the results of the simulations there is the basic output data given by MOHID Studio, like velocity components or water lever. Nevertheless some other parameter where interesting to visualize so they have been programed. They are written in the same way as the Time Series Files (this files are results of parameters that the user wants to track during the simulation and they are plotted in a x-y graph). In the appendix A.1 is explained the input data required for this implementation, where it has to be written the specific keyword in order to print the output data. The parameters plotted will be three, power of the turbine, energy extracted and velocity of the flow in the turbine cell. This three parameter are plotted for each turbine selected and for the total. In other words, you can plot the power and energy extraction of the array of turbines that you are simulating and of single turbines also, simultaneously.

3. RESULTS

In this chapter the results of different simulations are presented. The idea is to verify the implementation comparing different results and to show its potential with analytic data. The results shown here are already in a stabilized and stationary situation. In the 3D simulations, the vertical discretisation is made with Sigma coordinates.

Simulation	DT [s]	2D/3D	Vertical discretisation	Grid size [m]	Nº turbines
Horizontal channel	1	3D	25 layers equidistant.	20	1
Diagonal channel	1	3D	25 layers equidistant.	20	1
Array layout	1	2D	-	20	14
Real case	20	2D	-	300	40

Table 1. List of simulations. Own source

3.1. GENERAL SETUP

The basic (axial) turbine parameters will be the same for all the simulations in order to simplify and allow the comparison of the different simulations. Only some variations will be made in the cut-in speed and design velocities and in the diameter for the real case simulations. Any change of this values will be specified. The thrust and power coefficient will be the same in all the simulations.

Turbine set-up	
Diameter	20 m
Power coefficient (C_{Po})	0.40
Thrust coefficient (C_{T0})	0.85

Table 2. Basic parameters values. Own source

The C_P and C_T coefficient values adopted for the simulations are the ones suggested by Bahaj et al in his study [12].

3.2. SIMULATIONS

3.2.1. Horizontal channel

This simulation is a basic one in order to see the effect of the turbine in the horizontal and vertical planes: flow modification, water level and energy extraction. The bathymetry of the domain is constant, 40m depth, and the turbines are placed in a height of 20 meters respect the floor. The cut-in speed and design speed are 1 and 2.5 m/s respectively. The velocity imposed in the channel left side boundary is 3 m/s.

The flow field is illustrated from figure 11 to figure 13. The modification of the flow in both planes, horizontal and vertical meets the expectations of what the flow, in a macroscopic scale simulation, should do.

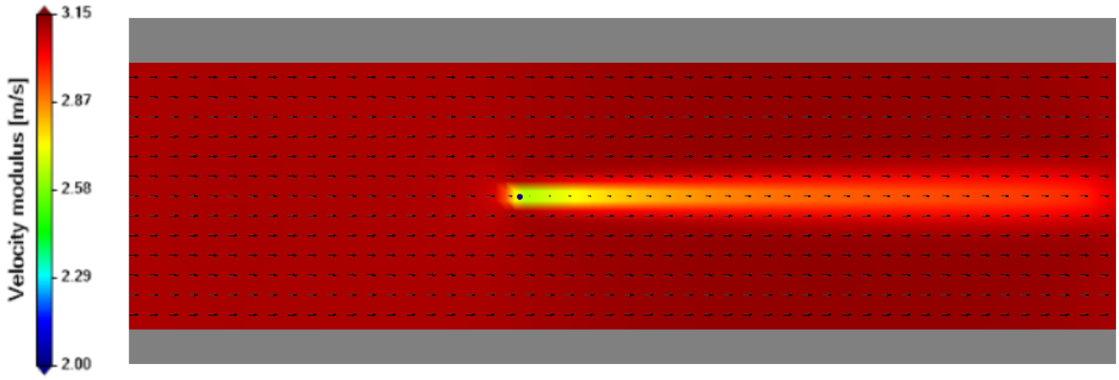

Figure 11 Velocity modulus in the horizontal plane in the layer 12, what represents a depth of 19.2 meters. Source: MOHID Studio

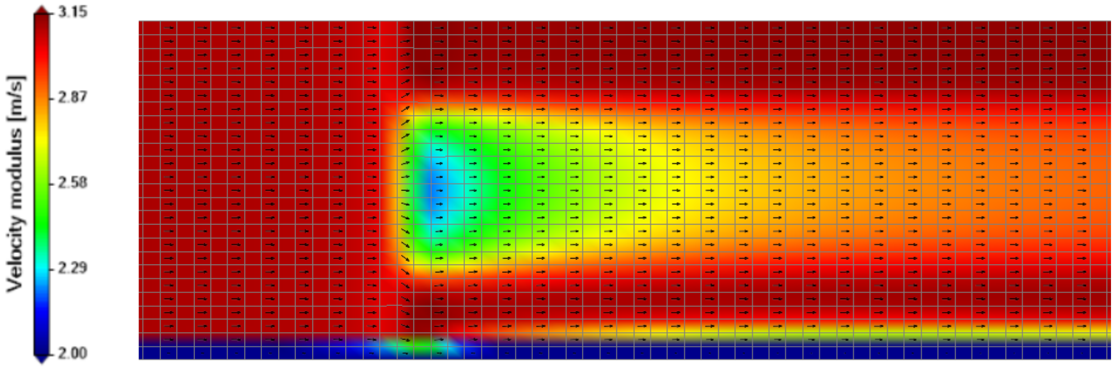

Figure 12. Vertical cut in the x axis of the flow field. In order to provide a better visualisation, a certain distortion have been applied in the horizontal dimension of the grid. As the turbine is discretized in the vertical domain, the resolution in the vertical is better than in the horizontal. Source: MOHID Studio

In the figure 12 can be appreciated how the flow modification provoces high velocities in the floor just under the turbine. As can be expected, this variation of flow velocities provoques a variation on sediment diposistation and erosion. This shows a subconsequence result of current turbines.

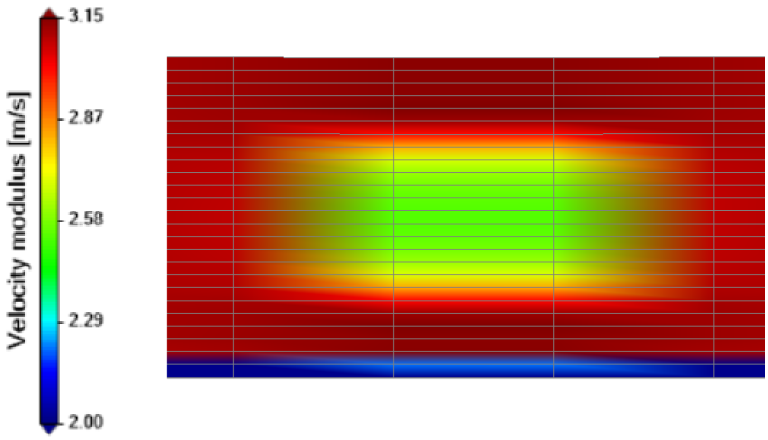

Figure 13. Vertical cut in the y axis, frontal view of the turbine. Source: MOHID Studio

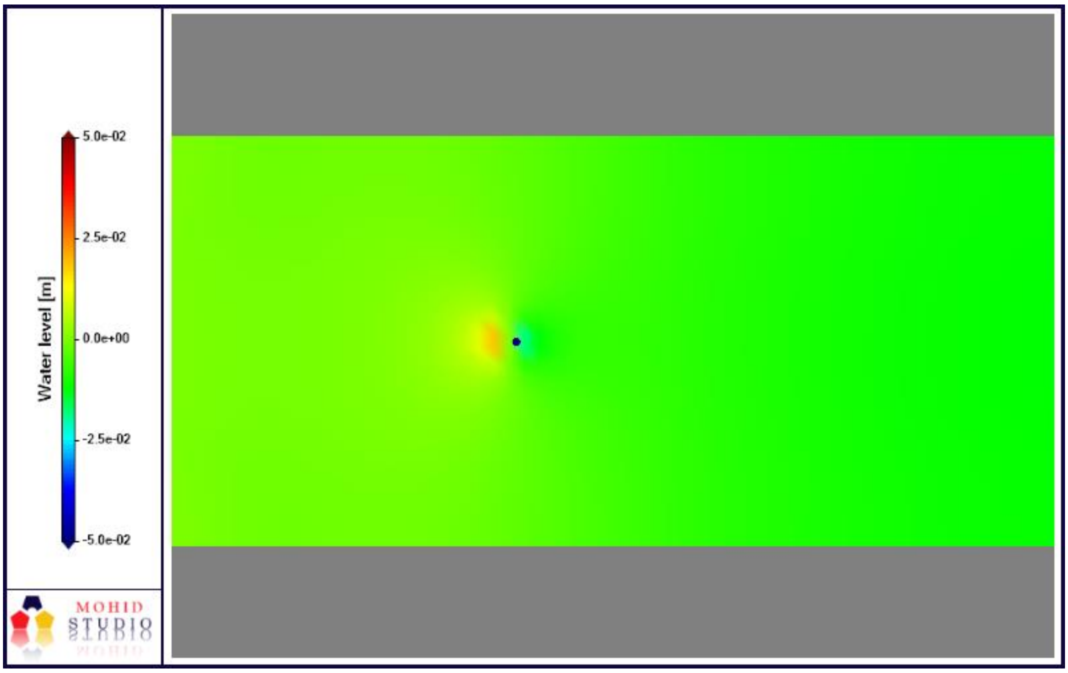

Figure 14. Effect of the turbine in the water level. This picture is made in the upper layer. Source: MOHID Studio

The effect of the turbine in the water level is small. As can be observed, upstream the turbine there is a slightly increase of the level while downstream the level decreases. For one turbine maybe de effect is almost inappreciable, but for an array of turbines is a consequence to take under consideration.

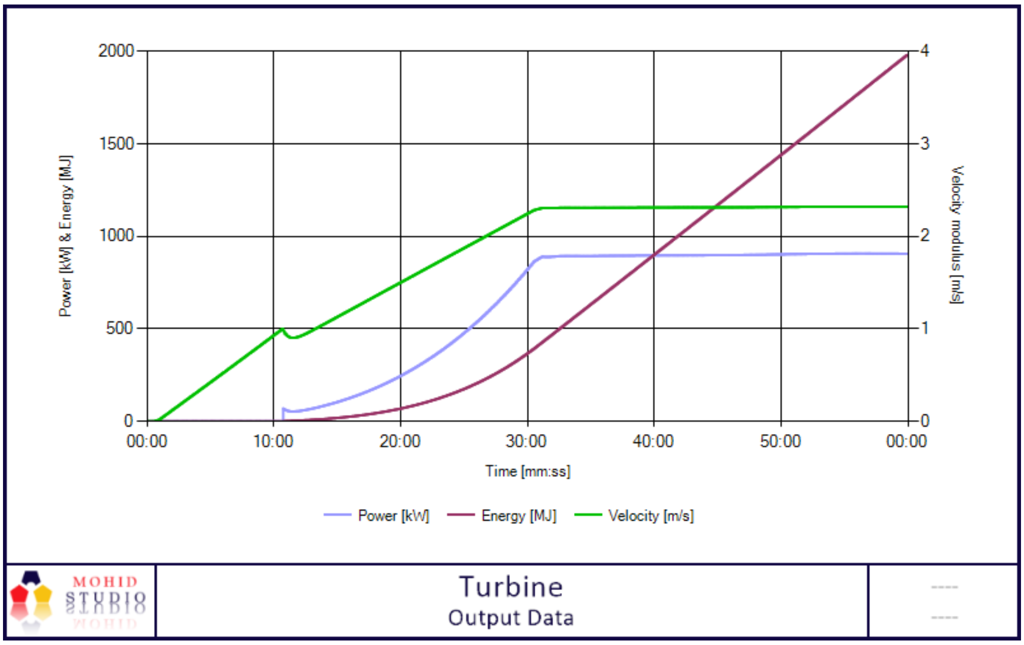

Figure 15. X-Y Graph of the velocity, power and energy output. Source: MOHID Studio

In this last figure, the effect of the turbine when the velocity of the stream surpass the cut-in speed can be clearly identified. Nevertheless, the effect when the pitch control starts and the thrust force and power decreases cannot be appreciated as the turbine hasn't reach the speed of 2.5 m/s at any point.

3.2.2. Diagonal channel

This simulation is the same as the one before but with a diagonal channel, to prove the robustness of the implementation and that it can give good results no matter the direction of the stream. The bathymetry is the same, 40 meters depth, and in this case the cut-in speed is the same as the one before (1 m/s) while the design speed is now 2 m/s to visualise the effect on the power output and the velocity. The velocity imposed to the left open boundary of the channel is 3 m/s with the same direction of the channel.

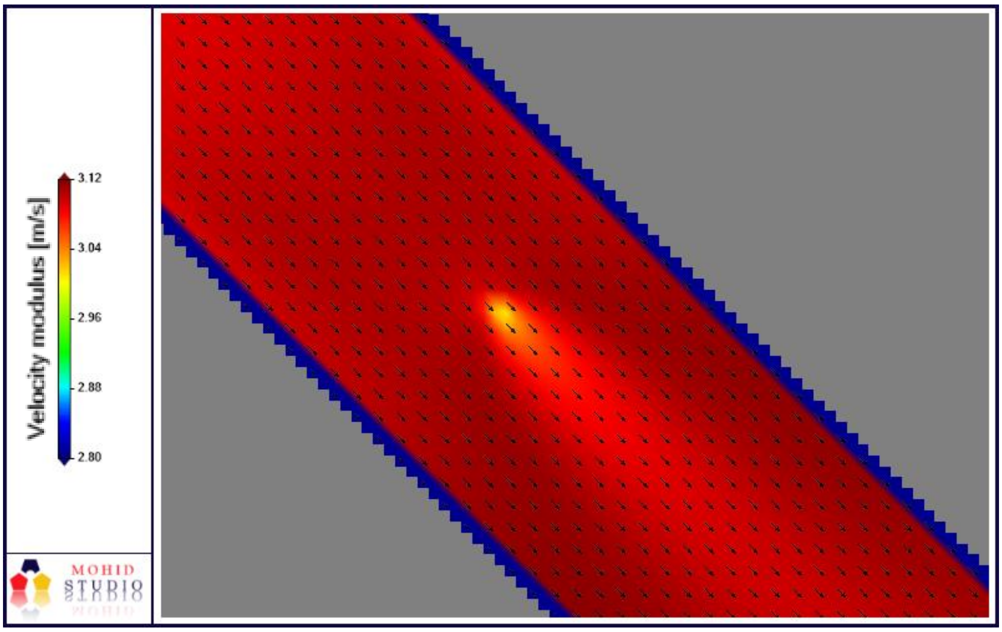

Figure 16. Velocity field in the layer 12 (19.2 metres depth). Source: MOHID Studio

In the figure 16 we can appreciate that because the design speed have been decreased, then the force exerted by the turbine decreases with the speed when it is over its design value. Is because of that that the turbine doesn't have so much effect in the fluid as in the previous case.

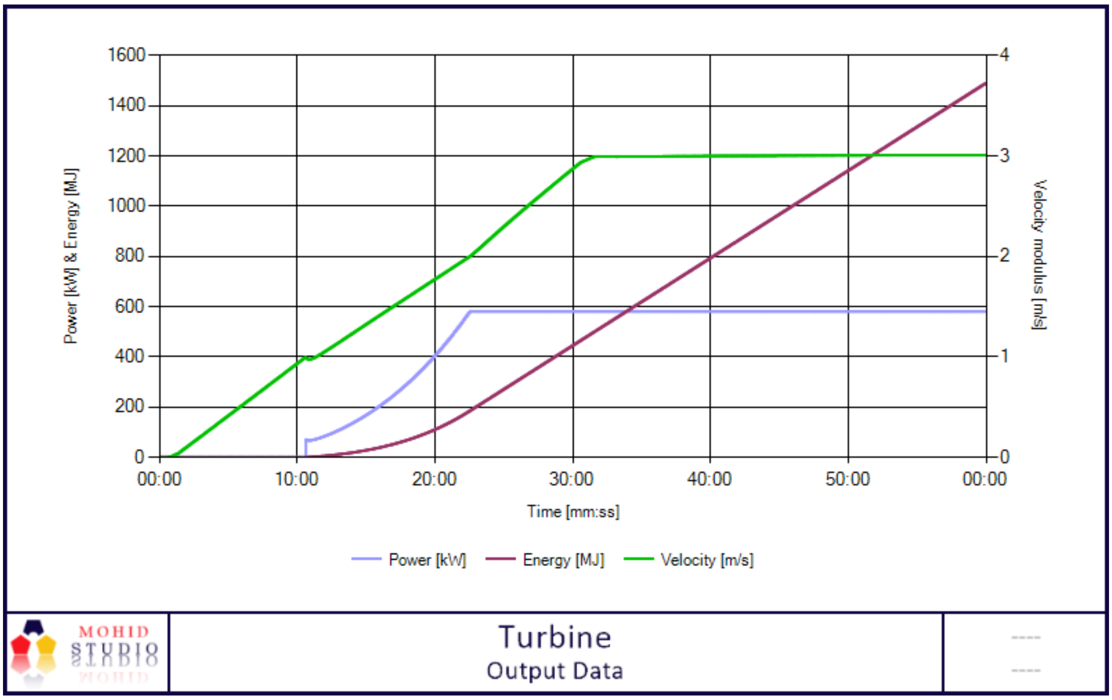

Figure 17. X-Y Graph of the velocity, power and energy output. Source: MOHID Studio

In this one, unlike the previous simulation where the velocity didn't reach the design value, here it does (because the design speed value have been decreased to 2 m/s). Here the cut-in speed and design speed points can be appreciated, as well as their effects in the velocities and power output. The effect of decreasing the speed design, compared with the figure 15 of the previous simulation, is an increase on the velocity passing through the turbine due to the effect of the parameterization of the thrust coefficient, which its curve is similar at the one expressed on the figure 7. And also the power output decreases significantly.

3.2.3. Array layout

The idea of these simulations is to show the capability of the implementation for array layout studies. Two different scenarios are contemplated, the main characteristics are the same, the only difference between them is the distribution of the turbines in the domain. The number of turbines is the same in both, 14.

The domain is a channel of 2 km long and 540 m width, same grid size in both cases and constant bathymetry of 40m depth. The velocity imposed of the current stream is 3 m/s. In this study, the design velocity value has been modified to 5 m/s (the value itself doesn't matter, it has to be higher than the stream velocity), higher than the maximum velocity in the channel in order to perceive the difference between both arrays layouts.

The first layout is a three-lined array (5 - 4 - 5). The y-axis distance between turbines is 20 m while the x-axis distance is around 80m. The second layout is a four-lined array (4-3-4-3) divided in two main lines with an x-axis distance of 160 meters. Both distributions can be appreciated in the figures 18 and 19 respectively.

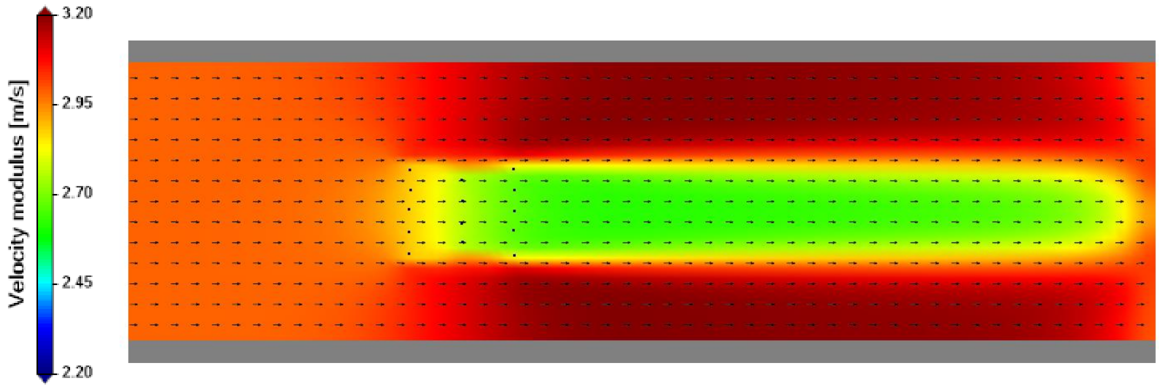

Figure 18. Velocity field for the layout 1. Source: MOHID Studio.

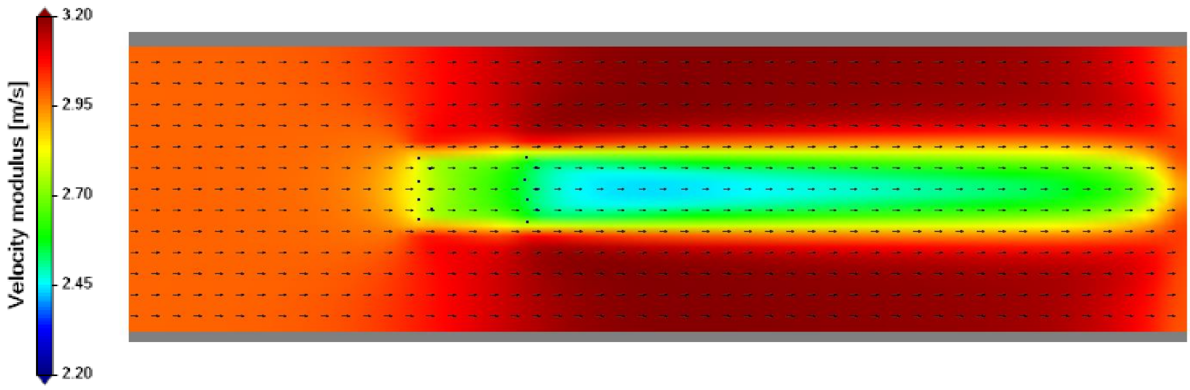

Figure 19. Velocity field for the layout 2. Source: MOHID Studio

Taking a look at the flow velocities, it can be appreciated how the second layout creates lower velocities after the two last lines of turbines. This is because the turbines aren't as separated in the y direction as in the layout 1, creating a blockage effect.

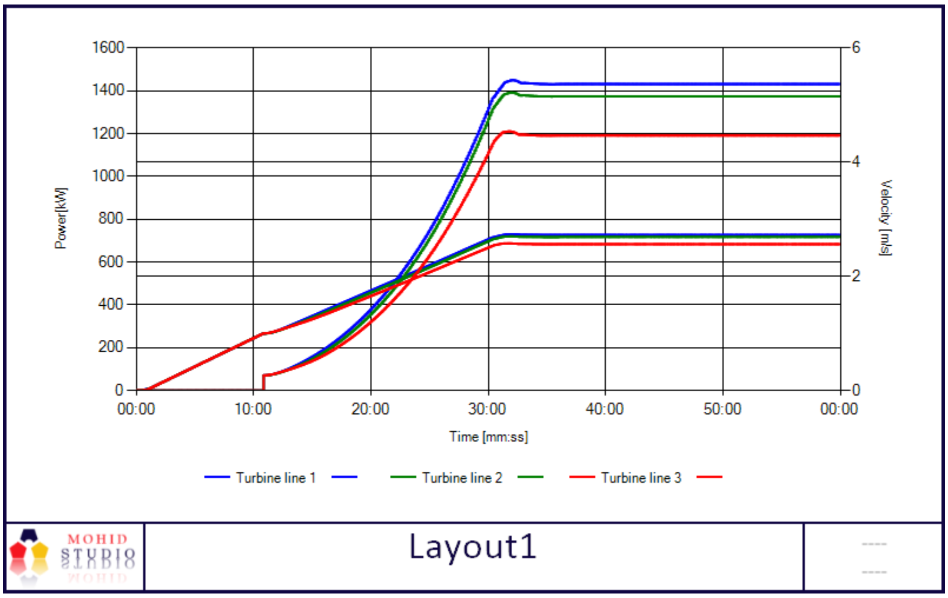

Figure 21. Power and velocity data for the layout 1. The values shown are from three turbines, one of each line of the array. Source: MOHID Studio

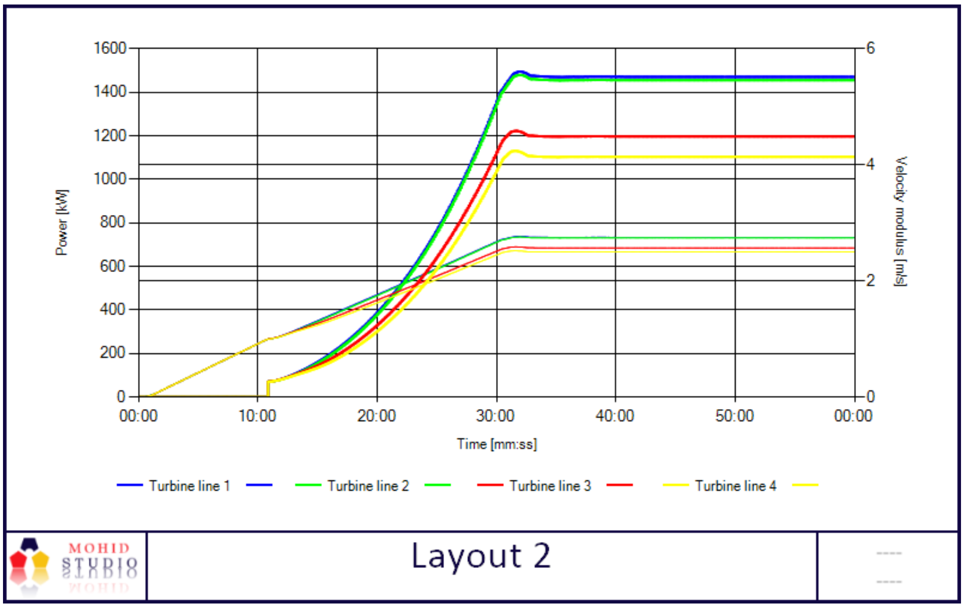

Figure 20. Power and velocity data for the layout 2. The vaules shown are from three turbines, one of each line of the array. Source: MOHID Studio

Both graphics shown the effect of the layout for each distribution in velocity and power output. The plot the values of velocity and power of one turbine of each line. In other words, represents the interaction between the turbine lines. For example, in the fig 21, you can notice how the effect of the line one of turbines verse the line two is almost inappreciable while the line 3 verse the line 4 is greater.

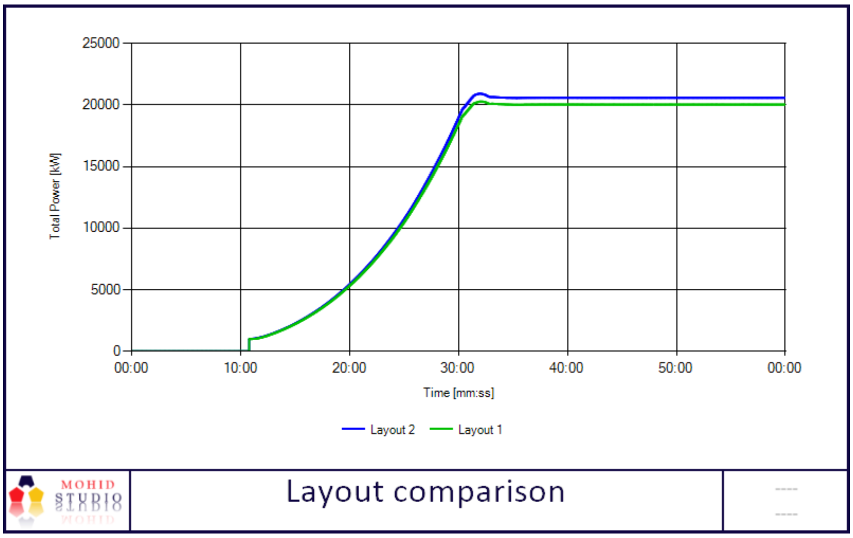

Figure 22. Total power extraction of both arrays. Numerically the layout 2 reach a maximum power output of 20.59 MW while the layout 1 reach 20.03 MW.

Finally, for comparing both layouts, the total power is plotted. The fig 22 reveals that the second layout is better in terms of energy extraction. Like this example, multitude of layouts can be studied and compared with individual values of the power outputs or either total values.

3.2.4. Real case

In this case the implementation is tested with a tidal simulation to see the results of energy extraction in a "real" scenario. Nevertheless, the visual data available for flow modification is not accurate because of the low resolution of the simulation (the size of the cell is quite big in comparison with the other simulations). So, taking advantage that the implementation allows to put more than one turbine per cell, this simulation will emulate a turbine farm. Instead of defining an array of turbines, a density of turbine per cell will be defined. In this case, considering that the cells where we will place the turbines have the approximate size of 300x300m, we will place in 4 cells a total of 40 turbines, 10 turbines in each cell.

The emplacement chosen to make the simulation is the Tagus Estuary (fig 23). Is not an idyllic emplacement to install tidal turbines because the current streams are weak and the bathymetry of the estuary is not too depth. But for the purpose of testing the implementation in low resolution grids it will be enough. The emplacement chosen has enough depth to handle little turbines of 10 meter diameter. The cut-in speed has been changed to 0.5 m/s and the design velocity to 1.0 m/s.

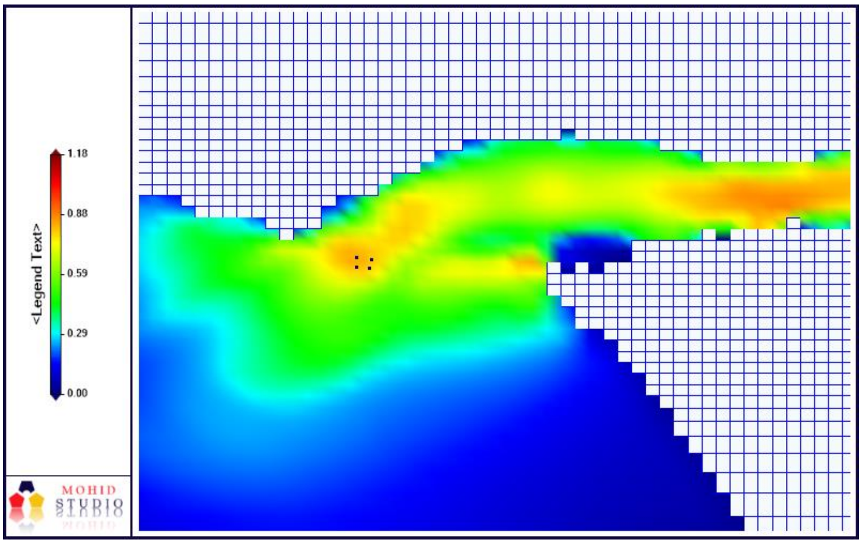

Figure 23. Placement of the turbines in the Tagus Estuary. Each point represents one group of 10 turbines, and each group is placed in a cell of 300x300m. Source: MOHID Studio.

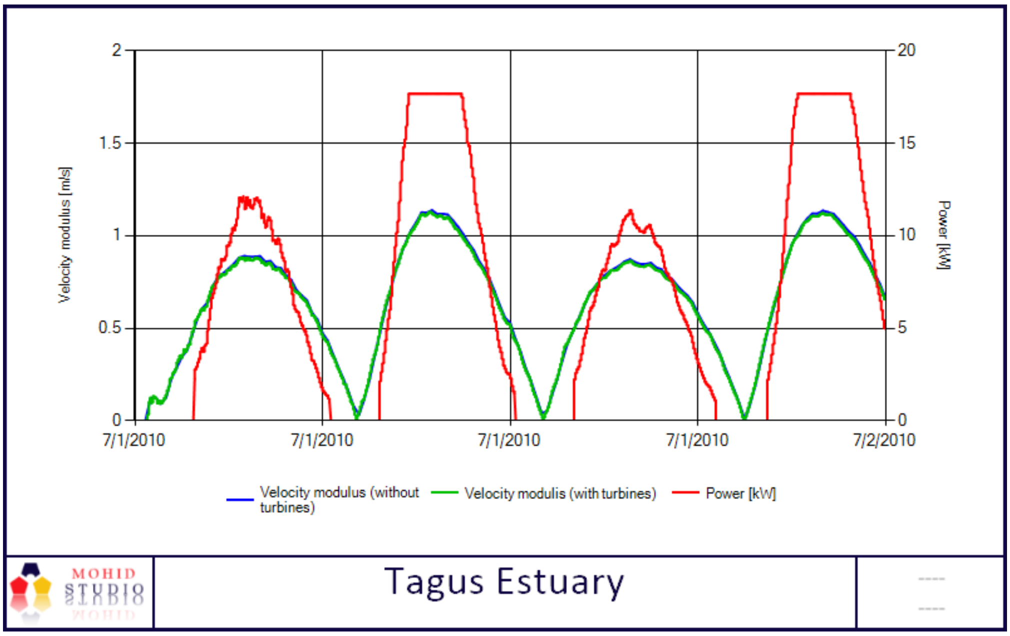

Figure 24. Power and velocity output of one group of 10 turbines. Source: MOHID Studio

In this graph (figure 24) the actuation of cut-in and design velocities can be appreciated in the power curve. Also the effect of the turbines in the velocity is slightly appreciated (difference between the blue and green line). Even if the study case is not realistic, the total power and energy output for the 40 turbines is presented in the figure 25.

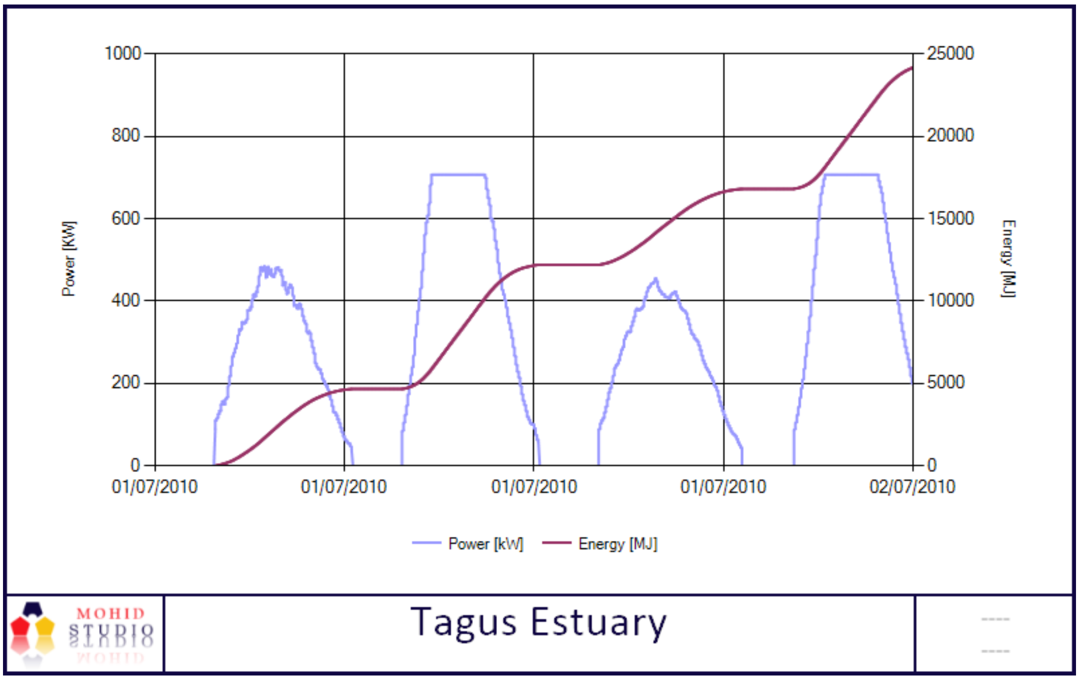

Figure 25. Energy and power output of the 40 turbines placed in the Tagus Estuary. Source: MOHID Studio

4. CONCLUSION

4.1. ACHIEVEMENTS

A good compromise between the computational cost and the results have been achieved. The implementations capabilities are quite good and allow some interesting studies of energy extraction, array layout and flow modification.

The implementation is a reliable and simple model of the effect of turbines inside a realistic and complex three dimensional hydrodynamic model. The objectives proposed have been achieved in a proper way, and some good ideas have appeared due to the realisation of this project.

4.2. LIMITATIONS

The origin of the main limitations of this implementation is the non-discretisation in the horizontal plane.

The implementation is not programed to work with really small grid size, the results will be always inappropriate when the cell size is under the turbine diameter thought there is no discretisation. Also it is not prepared to work with really large grid size, because visual data doesn't show significant changes due to the resolution and also the calculation are not really accurate.

Another limitation derived of the horizontal discretisation is the layout array studies. Actually there are some limitations with the distances and positions between the turbines because the minimal distance between them will be, at least, as big as the grid cell size diameter. These are the main limitations of the implementation.

4.3. FUTURE WORK

After the different basic simulations are done, the implementation is ready to be tested in a real environment with more complex simulations. The next thing to do is to test it in a real case where the results can be compared with real data. In this case, it will be of great interest to squeeze the potential of MOHID and work with nested models. Nested models are the perfect tool for solving the resolution problem derived of the difference in scale of the different processes involved as happens with tidal energy: tides and turbines. The idea is to have a high resolution (the grid size of the nested model should be as small as the turbine rotor diameter with the actual implementation) where the turbines are placed, and work with lower resolution in the rest of the domain. Also it will be interesting to test the implementation with the sediments transportation to see how turbines array can affect on it in long term simulations. It is a real interesting study to do in order to contribute with some data to the environmental impact of this kind of technologies.

Apart from testing the implementation, there are some improvements that can be done. First of all, and the most suitable one, is to improve the input data format in a more accessible and efficient way. Actually, if the user needs to work with large arrays of turbines, he will spend a good time to configure it, in the apendix A.1 the actual format of input data is explained. The easiest way to do it is to link the input data of the turbines with a xyz format file where there will be only the location of the turbine. This is interesting thought MOHID actually provides a tool to place points in the map and saves them in this kind of files. The model will read the basic and common parameters (thrust and power coefficients, dimensions, etc) in one file, and the locations in another file. This also restrict the model in the way that all the turbines will have the same basic parameters, but in the other hand makes the creation of input data more efficient.

The second improvement is to implement the horizontal discretisation with the purpose of overcome the limitations exposed in the point 4.2. The approach proposed next have not been programed because there were some complications in the transformation of the input data to the discretized geoometry, which is considered the main issue. The idea of this implementation is to use a similar input data file and the implementation is the one in charge of creating the geometry of the turbine in the domain, either in 2D or 3D simulations.

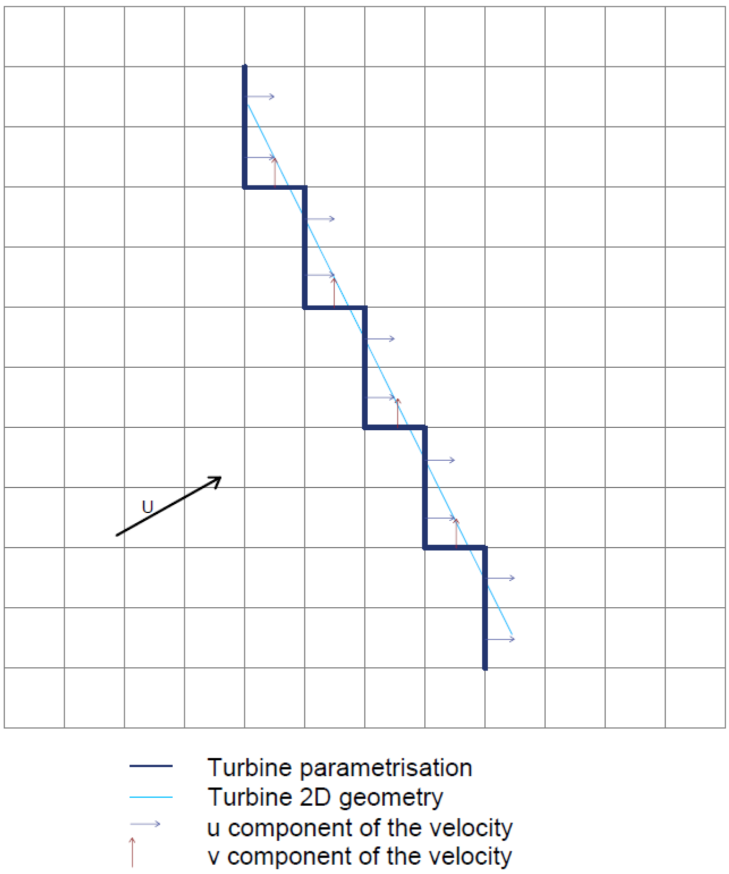

Figure 26.Example of 2D discretization. Own source.

The figure 26 shows a possible discretisation of the turbine in the 2D domain. This discretisation only computes the u and v components of the velocity in some cells, in order to not duplicate the effect. To make this discretisation having only the location and the diameter of the turbine, we need to draw the parameterisation perpendicular with the velocity direction, and then make the discretisation in the domain. Here the calculation of the modulus of the velocity for computing the force should be calculated as the option 2 presented in the point 2.2.3. For the power output and energy the velocity modulus can be an average as it's done in the vertical direction in the actual implementation.

Also the direction of the turbine should be corrected in case that the velocity direction changes because in this model the perpendicularity is not assured. The direction of the turbine can be obtained with the sum of the longitude of the faces where the u component of the velocity is computed and the longitudes of the cells where the v component is computed. With this we can check if the perpendicularity between velocity and turbine is conserved during the simulation and correct the geometry in case that the deviation is significant.

For the 3D model, the discretisation will be in both vertical and horizontal domains, so the drawing of the turbine will be similar to a circumference. The actual vertical discretisation will be useless in this model, so a new one should be made, applying the force to all the cells surface that are in a distance from the turbine position lower than the radius. Nevertheless, once the horizontal discretisation is made, the vertical should be more easy because the i and j values of the cells affected are the same as in the ones discretised in the horizontal domain, only the k dimension should be determined with the rule of the distance to the centre of the turbine.

The future implementation presented in this point is expected to work properly with high resolution grids in a range of five to ten times less the turbine diameter. It has to be taken into account that this implementation, if it wants to be used in tidal simulations with real environments, the computational cost could be really high. Variable grids or nested domains can release the heaviness of the calculations. With the implementation described, a good resolution to take advantage of it will be in the scale of 1 meter while normally, in hydrodynamic coastal studies the grid size is not lower of 10 meters.

There is still work to do to improve the implementation, and much more work to do to achieve the goal of a sustainable future for the energy system. This project, in the humblest way possible, tries to become a tool implemented in the MOHID Studio application in order to boost current energy extraction, embracing the philosophy of MOHID as a modelling decision support tool that it is today.

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APPENDIX A

A.1. INPUT DATA

The input data format is where the list of the turbines and their parameters have to be specified. The data is organized with the following keywords:

Global keywords		
Keyword	Default value	Description
TIMESERIE	0	This is the global parameter of the output files, if you want to write any output of any of the turbines this parameter should be 1, if not, 0.
<beginturbinelist>	-	Indicates the begin of the turbine list.
<endturbinelist>	-	Indicates the end of the turbine list
<<beginturbine>>	-	Indicates the start of the parameters of a single turbine
<<endturbine>>	-	Indicates the of the parameters of a single turbine
Specific keywords		
DIAMETER	-	The diameter of the turbine, in meters
HEIGHT	-	The heigh of the centre of the turbine respect the floor, in meters
CP	-	Power coefficient value
CT	-	Thrust coefficient value
LOWER_VEL	0	Cut-in speed, in m/s
UPPER_VEL	10	Design speed, in m/s
POS_LONG	-	Longitude position in geographic coordinates and x position in metric coordinates.
POS_LAT	-	Latitude position in geographic coordinates or y position in metric coordinates.
TIMESERIE	0	1: activates the timeserie module and prints the output data of the turbine 0 : no output data

Table 3. Input Data keywords. Own source

An example of input data will be:

```
TIMESERIE        : 1

<beginturbinelist>
<<beginturbine>>
DIAMETER         : 20
HEIGHT           : 20
CP               : 0.45
CT               : 0.85
LOWER_VEL        : 1
UPPER_VEL        : 2
POS_LONG         : 789.70291822
POS_LAT          : 988.39745136
TIMESERIE        : 1
<<endturbine>>

<<beginturbine>>
DIAMETER         : 20
HEIGHT           : 20
CP               : 0.45
CT               : 0.85
LOWER_VEL        : 1
UPPER_VEL        : 2
POS_LONG         : 729.70291822
POS_LAT          : 988.39745136
TIMESERIE        : 1
<<endturbine>>
<endturbinelist>
```

Figure 27. Example of input data. Own source

A.2. MOHID CONFIGURATION FILES

In order to activate the implementation, some modifications need to be done to the main configuration files. Two files need to be changed, the hydrodynamic.dat file and the nomfich.dat.

In the hydrodynamic file the keyword TURBINE needs to be written with a value of 1 for activating the implementation. If it is not written or with a value of 0 it will not work.

Hydrodynamic_1.dat

```
!ADV_METHOD_V              : 1
!TVD_LIMIT_H               : 4
!TVD_LIMIT_V               : 4

!VOLUME_RELATION_MAX      : 1.3

CORIOLIS                  : 0

NONHYDROSTATIC            : 0

TIDE                      : 0
WIND                      : 0
WATER_DISCHARGES          : 0
MOMENTUM_DISCHARGE        : 0
BAROCLINIC                : 0

TURBINE                   : 1

DATA_ASSIMILATION         : 1

RADIATION                 : 2
```

Figure 28. Example of hydrodynamic file with the implementation activated. Own source

The file Nomfich.dat is where the routes of the files needed for the simulations are specified. So, in order to make the implementation work and that the model can read the input data of the turbines, this route should be written in this file. The keyword for this file is TURBINE.

```
IN_BATIM                 : D:\MOHID Water Quick Start Guide\Projects\11Set\General Data\Digital Terrain\gridData.dat
ROOT                     : D:\MOHID Water Quick Start Guide\Projects\11Set\res
ROOT_SRT                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Run1\
SURF_DAT                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Atmosphere_1.dat
SURF_HDF                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Atmosphere_1.hdf
DOMAIN                   : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Geometry_1.dat
IN_DAD3D                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Hydrodynamic_1.dat
OUT_DESF                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Hydrodynamic_1.hdf
OUT_FIN                  : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Hydrodynamic_1.fin
BOT_DAT                  : D:\MOHID Water Quick Start Guide\Projects\11Set\data\InterfaceSedimentWater_1.dat
BOT_HDF                  : D:\MOHID Water Quick Start Guide\Projects\11Set\res\InterfaceSedimentWater_1.hdf
BOT_FIN                  : D:\MOHID Water Quick Start Guide\Projects\11Set\res\InterfaceSedimentWater_1.fin
AIRW_DAT                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\InterfaceWaterAir_1.dat
AIRW_HDF                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\InterfaceWaterAir_1.hdf
AIRW_FIN                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\InterfaceWaterAir_1.fin
IN_MODEL                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Model_1.dat
IN_TIDES                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Tide_1.dat
IN_TURB                  : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Turbulence_1.dat
TURB_HDF                 : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Turbulence_1.hdf
DISPQUAL                 : D:\MOHID Water Quick Start Guide\Projects\11Set\data\WaterProperties_1.dat
EUL_HDF                  : D:\MOHID Water Quick Start Guide\Projects\11Set\res\WaterProperties_1.hdf
EUL_FIN                  : D:\MOHID Water Quick Start Guide\Projects\11Set\res\WaterProperties_1.fin
ASSIMILA_DAT             : D:\MOHID Water Quick Start Guide\Projects\11Set\data\Assimilation_1.dat
ASSIMILA_HDF             : D:\MOHID Water Quick Start Guide\Projects\11Set\res\Assimilation_1.hdf
TURBINE                  : D:\MOHID Water Quick Start Guide\Projects\11Set\data\TurbineParameters_1T.dat
```

Figure 29. Example of Nomfich.dat file with the turbine input data path included at the end. Own source